Magma Densities, Magma Reservoirs, and Volcanic Eruption Styles on Io.
Giovanni Leone and Lionel Wilson, Environmental Science Division, Institute of Environmental and Biological Sciences, Lancaster University, Lancaster LA1 4YQ, U.K.

Uncertainties about the compositions of magmas currently erupting on Io, and about the compositions and amounts of volatiles that they exsolve, have prompted us to compute bulk densities for a wide range of magma-volatile combinations as they approach the surface. We thus explore the influence of the crustal density structure on magma rise and so predict likely depths of intrusions and evolving magma reservoirs. We also comment on the phreatomagmatic interactions between magmas and surface/near-surface volatiles.

Many aspects of the volcanic activity on Io are still uncertain. Neither the compositions of silicate magmas approaching the surface from the mantle nor the compositions of magmatic volatiles they release are well-constrained by observations. The conventional picture is that basaltic magmas [3] interact to varying degrees with surface deposits, or with shallow layers or aquifers of SO_2 and/or sulphur, to generate the range of eruption styles and volcanic features seen. Presumably the surface sulphur compounds are the accumulated products of magma degassing throughout the history of Io. The recent discovery of an iron/iron sulphide core in Io [5] would be consistent with a peridotitic mantle which generates basaltic magmas exsolving sulphur at pressures as high as 2 GPa, corresponding to a depth of ~300 km on Io. However, there is no guarantee that sulphur is the currently dominant magma volatile, an issue underlined by the recent detection of an absorption band possibly due to small amounts of surface water ice [1]. For basaltic magmas reaching the surface, the main source of H_2O in the mantle could be the magnesian mica phlogopite, which is also a potential source of the potassium [2] in Io's torus (and of radioactive heating in the mantle). If the mantle of Io has been sufficiently well processed during its history, however, much more evolved, and less dense, andesitic or rhyolitic melts could be common [4]. With these issues in mind, we have calculated the bulk densities of magmas with a wide range of liquid compositions and volatile contents and species as they approach shallow depths on Io in order to examine their potential interactions with solid or liquid volatile layers. Some of the trends found are illustrated in Table 1.

For a wide range of depths below the surface, we show the possible crustal density structure. We list the densities of SO_2 and sulphur over the range of depths (and hence temperatures and pressures) for which they are solids, and we show the density of the crust which would evolve from repeated basaltic eruptions, i.e. a pile of vesicular or fragmental basaltic crustal rocks compressing with depth under their own weight (as used to model the location of density traps and magma neutral buoyancy zones in the Venus lithosphere [6]). The densities of these three model crusts are not sufficiently different over the first kilometer (where the actual crust of Io is presumably some combination of these components) to make a significant difference to the pressure, and hence density, distribution at greater depths.

These crustal densities are compared in Table 1 with those of three model magmas. Because of the uncertainty in the composition of possible magma volatiles we use the pressure-dependent solubilities of H_2O and CO_2 in basaltic magmas [7] as illustrations of a relatively soluble and a relatively insoluble species. The assumption of a basaltic melt is not critical to what follows, but it is appropriate that the same composition is used for the rising melt and the surrounding crust to ensure that the melt is buoyant at great depths where no volatiles have yet been exsolved (we leave scenarios in which the melt is negatively buoyant at great depth and is driven upward by an excess pressure in the magma source region for future consideration). Three combinations of volatile composition and pre-eruption magma volatile content are used in the table: 0.3 wt% and 1.0 wt% of a high-solubility volatile represented by H_2O and indicated (H), and 0.3 wt% of a low-solubility volatile represented by CO_2 and shown as (L). We regard volatile amounts in this range as being plausible [8] unless the mantle of Io is now severely depleted of volatiles.

The following patterns are evident. All the magmas are positively buoyant at great depths. Gas exsolution in the case of the low solubility example and lack of crustal compaction in the case of the high-solubility examples cause the magma to become negatively buoyant at depths of 15 to 16 km. There is therefore the potential for ascending melts to stall and form magma reservoirs centred in this depth range. The magmas are then negatively buoyant over a wide depth interval, only becoming positively buoyant again (due to sufficient volatile exsolution) at depths which range from 2 km to 300 m, the value depending strongly on both the amount of volatile and its solubility. This means that, if magma density alone were the controlling factor, the roofs of the magma reservoirs could be located at depths as shallow as 1-2 km, allowing the possibility that the reservoirs could have half-heights (and thus, if they were of equant shape, typical radii) in excess of 10 km. This suggestion is at least consistent with the sizes of large caldera-like structures seen in Voyager images and also with the probable need for large magma reservoirs to supply the longer-lived eruptions. In fact, the conditions determining the maximum vertical extents of magma reservoirs are more complex [9], but not to the extent of invalidating the above analysis.

Finally, note that two of our three magma-volatile combinations are positively buoyant at the depths where they might encounter surface layers of SO_2 and/or sulphur (as solids or as liquids contained in silicate pore spaces), thus encouraging vigorous (phreato-magmaticexpl-osive) interaction between magma and volatiles. The third combination is negatively buoyant, allowing for possible intrusions producing the equivalents of hyaloclastites or pillow lavas.

References: [1] Salama, F. et al. (1994) Icarus 107, 413. [2] McBirney, A.R. (1993) Igneous Petrology, p. 250. [3] Carr, M. H. (1986) JGR 91, 3521. [4] Keszthelyi, L. & McEwen, A. S. (1996) EOS 77, F445. [5] Schubert, G. (1996) EOS 77, F442. [6] Head, J.W. & Wilson, L. (1992) JGR 97, 3877. [7] Wilson, L. & Head, J.W. (1981) JGR 86, 2971. [8] Lofgren, G. et al. (1981) Basaltic Volcanism on the Terrestrial Planets. [9] Parfitt, E.A. et al. (1993) JVGR 55, 1.

Table 1. Crustal density and pressure structure of Io, and bulk densities of three ascending model magmas (see text for descriptions). Densities of solid SO_2 and sulphur and of vesicular/fragmental basaltic crustal rocks compressing with depth under their own weight are shown in columns 3, 4 and 5; column 2 shows the implied pressure as a function of depth. Columns 6-11 show magma bulk densities and indicate positive (P), negative (N) or neutral (-) buoyancy.

depth in meters	pressure in MPa	crust density in kg m^{-3} SO_2	S	basalt	0.3% (H)		1.0%(H)		0.3%(L)	
					- - - bulk magma density in kg m^{-3} - - -					
3	0.01	1700	2000	2202	22	P	6	P	21	P
10	0.03	1700	2000	2204	65	P	19	P	63	P
30	0.09	1700	2000	2205	191	P	58	P	179	P
100	0.26	1700	2000	2207	518	P	163	P	459	P
300	0.78	1700	2000	2214	1246	P	455	P	1021	P
1000	2.9	-	2000	2236	2361	N	1255	P	1848	P
2000	8.0	-	-	2267	2600	N	2052	P	2281	N
3000	12.2	-	-	2297	2600	N	2317	N	2391	N
4000	16.3	-	-	2326	2600	N	2459	N	2447	N
5000	20.5	-	-	2354	2600	N	2549	N	2482	N
10000	42.3	-	-	2477	2600	N	2600	N	2556	N
15000	65.1	-	-	2577	2600	N	2600	N	2580	N
16345	71.3	-	-	2600	2600	-	2600	-	2584	P
20000	88.6	-	-	2655	2600	P	2600	P	2591	P
25000	112.8	-	-	2716	2600	P	2600	P	2597	P
28585	130.4	-	-	2751	2600	P	2600	P	2600	P
30000	137.5	-	-	2762	2600	P	2600	P	2600	P
40000	187.8	-	-	2824	2600	P	2600	P	2600	P
∞	∞	-	-	2900	2600	P	2600	P	2600	P